FINAL PROJECT REPORT
U-05-SC-058

PROJECT TERM: 06/01/06-06/30/13 (INCLUDING NO-COST EXTENSIONS)

PROJECT TITLE: HOW ABIOTIC PROCESSES, BIOTIC PROCESSES, AND THEIR INTERACTIONS SUSTAIN HABITAT CHARACTERISTICS AND FUNCTIONS IN RIVER CHANNELS AND THEIR FLOODPLAINS: AN INVESTIGATION OF HOW A REACH OF THE MERCED RIVER RESPONDS TO RESTORATION

AMOUNT FUNDED: $1,400,000

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PROJECT SUMMARY (ANY FORMAT)

The project used a restored reach of the Merced River to quantify long-discussed linkages between desirable biological responses and those physical characteristics of river channels and fluvial processes that are manipulated in river restoration projects. We focused on the 1.4 mile-long Robinson Reach of the Merced River, which had been rehabilitated as part of the Merced River Salmon Habitat Enhancement Project, managed by the California Department of Fish and Game, the California Department of Water Resources, the

CALFED Bay Delta Program, the U.S Fish and Wildlife Service, the U.S. Bureau of Reclamation, and the Robinson Cattle Company, which owns the land.

Some of the work focused on the Robinson Reach; other studies addressed the regional context of restoration efforts such as those being practiced in California's Central Valley; and other studies addressed fundamental theoretical questions in aquatic ecology with regional or global implications.

Research at the channel reach scale focused on four components of the restored ecosystem:

- channel and floodplain hydrology, hydraulics, sedimentation, and geomorphology to understand and predict how habitat qualities are created and change over time.
- relationships between the morphology, substrate and flow characteristics of channels and the availability of invertebrate food organisms and their delivery to fish.
- salmonid and other fish populations in the restored reach, and the development of models of fish growth
- colonization of the channel margins and floodplain by woody and herbaceous plants and the potential effect of woody debris on juvenile fish rearing conditions in gravel bed channels.

Research related to the regional scale (Central Valley of California) included a statistical survey of regional channel habitat characteristics. It was demonstrated that in the early post-construction years a particular project site can rapidly develop some regionally typical habitat characteristics. Channel and substrate characteristics affecting spawning are of this type, although continued channel evolution can also degrade these qualities if sediment supplies to the channel are limited. Other habitat characteristics, particularly those related to juvenile salmonid rearing are more demanding to design and implement, and they can take many years to develop unless steps are taken during construction to accelerate the process of creating them by artificial means. Modeling of habitat suitability and its role in providing bioenergetically favorable conditions for juvenile growth confirmed the results of the regional comparison. This combined hydrodynamic and bioenergetic model continues to be extended.

Research of a general theoretical nature included the initial development of a life-cycle bioenergetic model for computing the contribution of each life stage (development, growth and reproduction) to the successful maturation of any species of Pacific salmon. Implementation of the method in particular scenarios is still being developed.

BUDGET SUMMARY

Expense	Amount invoiced (1ST Year)	Amount invoiced (2ND Year)	Amount invoiced (3RD Year)	Amount invoiced (4th Year)	Amount invoiced (5th Year)	Amount invoiced (6th Year)	Amount invoiced (7th Year)	Amount invoiced to date (all years)
Salaries and Wages	$33,905.51	$175,121.29	$221,586.00	$32,296.67	$86,452.61	$164,065.96	$54,618.45	$768,046.49
Employee Benefits	$14,006.27	$50,464.27	$49,037.76	$12,465.53	$18,894.30	$40,727.34	$15,611.53	$201,207.00
Equipment & Facilities	$0.00	$0.00	$0.00	$23,087.74	$0.00	$0.00	$0.00	$23,087.74
Supplies, Materials & Services	$5,351.37	$14,438.18	$21,458.97	$5,529.18	$12,822.40	$14,383.08	$6,175.07	$80,158.25
Travel	$6,772.25	$23,689.12	$18,532.18	$2,603.73	$5,263.68	$5,625.66	$970.36	$63,456.98
Indirect Costs	$12,402.37	$59,528.07	$74,635.90	$11,270.38	$29,825.97	$56,201.26	$19,344.10	$263,208.05
Totals	$72,437.77	$323,240.93	$385,250.81	$87,253.23	$153,258.96	$281,003.30	$96,719.51	$1,399,164.51
Unbilled Balance								$835.49
Total Award								$1,400,000.00

TASK/SUB TASK	NAME	BUDGET
TASK 1	Coordination of Project	8,134
TASK 2	Hydrodynamics and Geomorphology: measurements	277,536
TASK 3	Hydrodynamics and Geomorphology: models	94,628
TASK 4	Surveys of invertebrate communities and their controlling factors	242,929
TASK 5	Surveys of fish communities	401,764
TASK 6	Bioenergetic-based models of fish	150,700
TASK 7	Floodplain vegetation studies	224,309
TOTALS		1,400,000

LIST OF TASKS AND ACTIVITIES PERFORMED (referenced to numbered publications and presentations listed below)

TASK 1: *Coordination of Project*.
The project was coordinated through meetings at UCSB, data sharing, and co-publication of journal articles. Coordination with CA Department of Water Resources occurred through occasional briefings, data sharing, and joint field surveys.

TASK 2: *Hydrodynamics and Geomorphology Measurements*.
Topographic, hydrometric, and sedimentological surveys were conducted to record habitat changes throughout the project, and especially to document hydrodynamic conditions during three large floods which caused virtually all the habitat change. These data were also used to calibrate and validate mathematical models of the evolution of the channel and its habitat quality, forming the basis for a number of journal articles referred to under other tasks. Three journal articles on theoretical aspects of channel and floodplain behavior were published (# PA 4,5,8 below); One is in preparation (# P1). Two articles were published on the regional hydrological and geomorphological context of the Robinson Reach restoration project and of fish extirpation in central California (# PA 1, 14). Five presentations were made at the Bay-Delta Science Conference (# BDS 1, 3, 5, 6,7) and 9 at other conferences (# OCR 1,2,3,4,5,10, 13,14, 15).

TASK 3*: Hydrodynamics and Geomorphology: models*
Hydrodynamic and geomorphological modeling was also carried out throughout and after the project to explain the physical reasons (a) for the observed habitat changes, (b) for expectations of what is likely to occur in the study reach in the future, (c) at other channel restoration sites, and (d) under other design scenarios. Effects of the hydrodynamics and the geomorphic changes on habitat quality were developed and implemented. One journal article was published on habitat evolution modeling (# PA 6; a second one is in journal review (# R1), and others are planned. Presentations were made at the Bay-Delta Science Conference (# BDS 3) and 5 at other conferences (# OCP 6,7,8,9,11)

TASK 4: Surveys of invertebrate communities and their controlling factors*.*

Field surveys of invertebrate communities were conducted in the project and adjacent reaches to understand factors controlling the primary food source for fish (as determined in #PA 13, 14). Three journal articles were published on this topic (# PA 2,12,13) and one presentation made at the Bay-Delta Science Conference (# BDS 2). Data from the invertebrate surveys contributed to the modeling of fish bioenergetics.

In preparation for the fish bioenergetic modeling, a "hybrid" approach was developed for simulating the spatial dynamics of macroinvertebrates in the Robinson Reach --- a key input to salmon bioenergetics models. Hydraulic predictions from the 2D model (developed in Task 3) were coupled with a particle tracking algorithm to compute drift dispersal, where the settling rates of simulated macroinvertebrates were parameterized from the literature. Using the cross-sectional averaged velocities from the 2D model, a simpler 1D representation of how dispersal distributions respond to flow variability was then developed. The 1D models allow simulation of much longer reaches of river and make fewer data demands than the more detailed 2D models (# PA 3; # OCR 12).

Insights and data collected on macroinvertebrates in the Robinson reach by Albertson and Cardinale (Task 4) were used with new basic theory to construct a model of dispersal of organisms in media such as rivers with strong advection (# PA 7; # OCR22; # R3).

TASK 5: Surveys of fish communities.

Surveys of salmon and non-salmon resident populations and their diets and growth were conducted in the project and adjacent reaches (# PA 10,12,13, #OCR 24), and experiments on salmonid egg survival were conducted in a local fish hatchery (#PA 11). Some of these results were used to parameterize and test models of dynamic energy budgets for salmon (# PA 9) and to test a model of the potential effectiveness of large woody debris on juvenile salmonid growth in gravel bed rivers that have been simplified in the course of restoration or other engineering activities (# R 1).

In order to test the results of the bioenergetic model of drift-feeding fish growth (Task 6) 60 cages (0.5 x 0.5 x 1.0 m) were installed in the Robinson Reach for a 30-day period of the juvenile Chinook rearing season. One Chinook salmon (~65 mm total length) was placed in each cage. Fish remained in cages four weeks and were measured and weighed at the beginning and end of the period. Growth rates of the recovered living fish ranged from 0.21 - 0.71 mm/d (0.50 mm/d average). During the same period 150 invertebrate drift samples were collected in order to provide a detailed estimate of the food available to the drift feeding fish in the reach. Weights and species composition of the food items were measured in order to estimate spatial and temporal patterns of invertebrate drift, to refine the parameterization of the model, and to examine stochastic characteristics of the food supply. Articles from this work are still being prepared.

TASK 6: ***Bioenergetic-based models of fish****.*

A salmon life-cycle model was developed to predict development, growth and reproduction of a Pacific salmon in a dynamic environment, from an egg to a reproducing female, and that links female state to egg traits (# PA 9 #OCR 16,17,18).

A second, higher-resolution bioenergetic model involved coupling a 2D hydrodynamic model (from Task 3) and a bioenergetic model of drift-feeding fish to quantify how habitat complexity generated by large woody debris affects the growth potential of juvenile Chinook salmon. Simulations indicated how LWD diversified the flow field, creating pronounced velocity gradients, which enhanced fish feeding and resting activities. Wood depletion in the world's rivers has been documented extensively, leading to widespread attempts by river managers to reverse this trend by adding wood to simplified aquatic habitats. However, systematic prediction of the effects of wood on fish growth has not been previously accomplished. The project developed a theory-based approach for assessing the role of wood on habitat potential for fish growth at the microhabitat and reach-scales. (# P 1 #OCR 23, 24). The work is now being extended by modeling 3D characteristics of the flow field around woody debris and the effects of permeability of the woody accumulations.

TASK 7: Floodplain vegetation studies*:*

The early post-construction degree of riparian vegetation was documented from DWR post-project monitoring and early UCSB surveys and reported at the Delta Science Conference (#BDS 4). Post-restoration groundwater tables were much deeper than expected based on pre-restoration conditions, which included extensive ponds in the pits left behind by mining. Surveys of seedling recruitment and interpretations of success and failure in relationship to the altered hydrology of the Merced River were also reported at conferences (# OCR 19, 20, 21), and in an article in review (# R2) and one in preparation (# P2). The study documented that although the prevailing recruitment box model for cottonwoods and willows in central California emphasizes pulses of dense recruitment and correspondingly high mortality rates along rivers with mobile banks, the Robinson reach and similar restoration projects are going to be characterized by sparse recruitment and low mortality on a managed stream with low bed mobility.

The significance of riparian zone plants for in-channel processes was highlighted at several stages of the other tasks in the study. Restoration of the Robinson Reach has significantly affected the structure of riparian and floodplain vegetation communities. Particularly important is the slow recovery of deciduous trees in the riparian zone, which have been shown elsewhere to account for a large portion of primary and secondary consumer biomass in lotic food webs. This lack of terrestrial input has the potential to influence both the structure of food webs in the restored reach and the distribution of consumers which was observed during the invertebrate monitoring (Task 4). Caddisflies, which filter dead organic matter (of both terrestrial and aquatic origin) from the drift are relatively more abundant in the unrestored reach upstream, where inputs of terrestrial carbon are greater, whereas algal grazing mayflies are relatively more abundant in the restored reach where terrestrial inputs are much smaller.

The modeling of the effects of large woody debris on juvenile Chinook growth potential (Task 6, # R2) also highlighted the potential for in-channel habitat quality improvements to be expected where mature woody riparian zone has been established to supply wood to the channel. Isotopes of carbon, nitrogen, and hydrogen from fish tissue samples collected in Task 5 (# PA 12,13) reflected the relative influence of the two riparian zones as food sources.

Funding from other sources

The original Calfed funding led to work being supported by three other grants:

1) California Energy Commission (subcontract from Instream Flow Assessment Program at UC Davis): *Integrating bioenergetics, spatial scales, and population dynamics for environmental flow assessments.* Award to R.M. Nisbet and K.E. Anderson (UC Riverside) - 9/1/09-12/21/10
2) NASA (subcontract from UC Santa Cruz) *From the Watershed to the Ocean: Using NASA data and models to understand and predict variations in central California salmon*. Award to R.M. Nisbet - 8/8/12-8/7/14
3) CA Department of Water Resources: *Analysis of the Potential for Gravel Augmentation in the Robinson Reach, Merced River*. Award to T. Dunne 3/1/2013-10/30/2013.

LIST THE ACHIEVED OBJECTIVES, FINDINGS, AND MAJOR CONTRIBUTIONS

Several disruptions to the project plans occurred in the earliest phase of the project, which forced major changes on the approaches and objectives of the project. First, developments in a court case elsewhere in California caused the landowner to delay access to the site until a contract could be negotiated with the UC Board of Regents indemnifying the company against liability for accidents. This delayed field research for a year. Next, the PI responsible for the largest part of the study, fish ecology and behavior, left to become the Lead Scientist for Calfed. His absence meant that there was no one to oversee field studies of these topics, and also that we were never able to get any agreement from the California Department of Fish & Game for permission to conduct field experiments in the sensitive fish habitat of the Robinson reach. Consequently, the focus of most of the biological work on the project was based (a) on sampling of diets and growth rates and (b) on modeling. Finally, the temporary suspension of state funding in 2009 forced us to lay off the four postdocs and one graduate student, and close the project. Some work continued as parts of the theses of graduate students funded by other means. When funding was restored, it took considerable time to recruit postdocs, and none of the biological postdocs stayed for long. All of these changes meant that field studies became limited in scope and duration, and experimentation had to be limited to a lab at UCSB and a fish hatchery. Modeling became a larger focus of the project. Our research interests in gravel particle mobility and substrate flow and temperature regime, which required installations in the stream bed were transferred to the San Joaquin River (with financial support from CADWR and Delta Science) where research permissions could be obtained. However, the following objectives, findings, and contributions resulted from the Merced project, as documented in the 14 publications listed below and others which continue to be produced through unfunded analysis and writing.

1. Hydrodynamics and Geomorphology

1.1 Objectives achieved

We were able to document and construct models of channel and floodplain habitat evolution, and to establish that the project habitat could only evolve episodically when unplanned, sustained overbank floods result from emergency flow releases from New Exchequer Dam. Our models allowed us to explain and predict the response of the channel and floodplain to high flows, alteration of sediment supply (including by artificial gravel augmentation), and the potential accumulation or installation of large woody debris. We have illustrated how such models can be applied in the design of future projects for predicting channel and floodplain responses to be expected with and without restoration. We have also demonstrated how by coupling a flow model with a habitat suitability models and bioenergetic models of fish growth, both in a channel and on a floodplain, interdisciplinary analyses of habitat quality in evolving geomorphic systems can be conducted for extending design practices.

1.2 Findings

The Robinson reach was designed to enhance the availability of spawning and rearing habitat. With our flow model we were able to model the habitat suitability for spawning and juvenile Chinook rearing and verify the accuracy of the predictions with field surveys of fish numbers and distributions. Flow and habitat modeling indicated that the availability of Chinook salmon spawning habitat increased over time as a result of bar growth due to sediment storage and bed erosion which lowered the gradient of riffles. However, the majority of the reach continues to provide only low- to medium-quality rearing habitat for juvenile salmonids, primarily because of a lack of low-velocity refuge zones. However, other metrics of flow complexity indicated that areas of favorable flow conditions gradually expanded as point bars developed along the inner bank of each bend.

The project demonstrated that, six years after construction, riffle habitats in the Robinson reach had flow discharge and depth, substrate and food web characteristics that are within the range of variability of other streams that support Chinook in the Central Valley. However, compared with other streams in the region, the restored reach still had minimal riparian cover, fewer undercut banks, less woody debris, and higher water temperatures, suggesting that these factors might still limit salmon habitat quality in the reach. The situation in the restored reach remained the same ten years after construction. Statistical analysis also demonstrated that for the same set of 19 rivers and the Merced salmon densities, measured by a variety of methods, tend to be greater in streams that have more undercut banks and woody debris and lower water temperatures. In the Robinson reach, these characteristics await further channel evolution and riparian tree growth.

The slow rate of increase in channel habitat complexlty is the result of both the reduction of sediment supply and the rarity of large floods in the postdam era. We were also able to link 2D and 3D hydrodynamic models with a bioenergetic model of juvenile Chinook growth to demonstrate the increases in juvenile growth that could result from the accumulation of large woody debris in the channel. Our models of channel evolution indicate that no foreseeable change in the rate of development of habitat complexity through sedimentation alone will provide sufficient flow complexity to significantly increase the value of the reach as juvenile rearing habitat.

Modeling of overbank flows indicated the potential for new channels to develop across the floodplain during flows 2-3 times bankfull discharge (with recurrence intervals greater than 5 years in the post-dam regime) . Although the coarse nature of the restored floodplain will slow the development of such channels in the Robinson reach, they are much more likely to develop quickly in finer- grained floodplains. This indication should provoke discussion amongst engineers and ecologists about the ecological value and safety of allowing such new channels to develop. It is possible to imagine that through such a process of avulsion there is the opportunity to allow a significant increase in the habitat complexity and ecological value of a valley floor. The models can also be used to indicate where intensive tree planting could be used to decrease the likelihood of such avulsions. This subject deserves further interdisciplinary research.

2. Aquatic Ecology

2.1 Objectives achieved
Interpretations of the trophic ecology of the reach for algal food sources, macroinvertebrates, juvenile Chinook salmon, and resident non-game fish were developed from sampling studies of occurrence, distributions, diets, and otolith-derived fish growth rates.

None of the planned studies of adult fish use of the reach were possible because of the absence of original PI Healey, for the reason explained above.

Progress was achieved with the modeling objectives at several scales.

The project demonstrated the essential accuracy of a habitat suitability model based on 2D flow modeling.

We also demonstrated the ability to model the evolution of channel habitat suitability using 2D modeling of flow, sediment transport, and channel bed change, including bank undercutting and bend migration, which were all slow during the three-flood decade of the study.

We also combined a 2D hydrodynamic model of channel and floodplain flows with a bioenergetic model of fish growth to assess how the area of habitat capable of supporting growth of juvenile fish to smoltification might be enhanced by additions of woody debris to a channel of any configuration, temperature and food supply. We expanded the modeling of channel flows to 3D to represent extra detail on the distortion of the flow field by the woody debris. The bioenergetic model of growth can be linked to our 2D floodplain flow model for use in floodplains where this process is ecologically important. Off-channel rearing habitat was not designed into the Robinson reach floodplain.

We could not obtain permission for an experimental field test of the model's prediction of how woody structure might favor growth rates, but the Robinson reach provides an excellent opportunity for such an experiment by other researchers with better connections.

Modeling of fish growth was also extended to the whole life cycle through the development of a Dynamic Energy Budget model of five Pacific salmon species, allowing the effects of environmental influences at one life stage, such as juvenile rearing, to be propagated through the entire life cycle. However, much work remains to be done to improve the parameterization of the model for individual life stages.

2.2 Findings
The project documented differences in benthic and planktonic invertebrate populations between the restored project reach, in which gravel (median size 55 mm) had been emplaced, and an adjacent, coarser-bedded reach with a median bed particle size of 70 mm and greater fines content. The adjacent reach had not been degraded by mining. Analysis of isotopic signatures suggests that macro invertebrates supporting fish populations as prey principally depend on diatomaceous algae in the restored habitat while filamentous algae were most important in the adjacent reach.

Experiments in a hatchery flume also documented that no differences in egg survival should be expected from the use of coarse, clean gravel for redd construction.

Although the project reach provided some rearing habitat for juvenile Chinook salmon and local resident fish, their overall densities were low, and they tended to be restricted to the downstream ends of point bars and the vicinity of a single piece of large woody debris. Nevertheless, growth rates of the Chinook juveniles, measured from otoliths matched or exceeded rates from some other Central Valley streams.

Habitat evolution in the Robinson reach is slow because of the limited frequency of channel-modifying flows and of sediment supply. Nevertheless, the reach does evolve in the manner expected with limited improvements to its habitat quality, but also with some negative developments such as the erosion of riffles and coarsening of the bed because of the steepness of the reach, imposed by the original valley gradient, and the small sediment supply from upstream. The implications of our modeling, however, are that significant habitat improvements are unlikely to take place in the foreseeable future as a result of flow and sedimentation processes alone.

Because of the modeled and observed limited area of juvenile rearing habitat, we combined 2D flow modeling and bioenergetic modeling of juvenile Chinook salmon growth rates to compute the in-channel area favorable to the rearing of a fish to smoltification size in the absence of predation. We then incorporated into the model various amounts of in-channel woody debris and computed the resulting increase in the area that could support juvenile growth to smoltification. The results were not intended to recommend whether or not such structures *should* be installed in the Robinson reach, but only to illustrate the principle that expansion of juvenile rearing habitat through the addition of in-channel structures could be modeled for use in planning future restoration projects. The modeling is now being extended through the use of 3D flow simulations and various alterations of the woody structures.

At a larger scale, the project developed a Dynamic Energy Budget model of all life stages of Pacific salmon that **"**closes**"** the life cycle in a realistic way. The model provides a realistic tool to help understand how the effects of changing environmental conditions affecting a specific life stage, such as spawning or in-channel growth, can propagate through the full life cycle of a Pacific salmon. Work is continuing to improve the parameterization of the model for particular life stages.

A result of more regional significance for fishery and river restoration in California was the statistical analysis of predictors of Chinook salmon extirpation in the Central Valley. The probability of extirpation in streams supporting autumn runs was predicted solely by migration barriers, whereas the probability of extirpation of spring-run populations depends also on habitat loss and altered flow regimes downstream of six Central valley dams, below which the autumn runs survive.

3. Riparian and Floodplain Plant Colonization.

3.1 Objectives achieved
Field surveys of herbaceous and woody vegetation were made and interpreted. However, the general sparseness of the re-vegetation and particularly of the original plantations limited the range and depth of analysis that was possible.

3.2 Findings
The project tracked herbaceous vegetation on the Robinson reach floodplain over the post-construction decade, building on early-stage monitoring by CADWR ecologists. Immediately after construction, combinations of three treatments had been applied to the floodplain: sowing a sterile cover crop, sowing native species, and inoculating mycorrhizae. We hypothesized that herbaceous communities would be structured by distance from the river, that the treatments would encourage native species, and that native

perennials would gradually outcompete exotic annuals. Instead, we observed a highly variable herbaceous community dominated by weedy exotics, including many annual grassland species. Composition sorted primarily into flood and non-flood associations unrelated to proximity to the river. Treatments were generally ineffective, but suggested that native perennials might be incapable of establishing naturally. Unlike typical riparian habitat, the Merced gravelly floodplain was effectively a dry upland terrace, more than 1 meter above the water table, which was controlled over most of the floodplain by the elevation of summer low flow in the channel. Thus, the moisture regime of the floodplain 'soil' was controlled by the limited water-holding capacity of the gravel and by local precipitation in most years with the effects of a spring flood occurring only every several years. Even after the flood, water tables fell rapidly in the gravelly floodplain sediment. These conditions suggest that , if re-built floodplains continue to be constructed with such coarse-grained material, the suitable restoration target might not include commonly restored native perennials, even if they can be artificially established. There is an opportunity for an extensive survey of the fines content and water-table depth regimes of floodplain alluvium in which native woody vegetation has rapidly colonized riparian and floodplain sites in the Central Valley. For ruderal and annual-dominated herbaceous communities like those that are colonizing the Robinson reach floodplain, the suitable target species for planting differ each year, requiring some re-consideration of planting strategies for particular sites.

DISCUSS THE MANAGEMENT IMPLICATIONS OF PROJECT FINDINGS

Scientific findings and interpretations can rarely be translated directly into implications for management because scientific studies are not subject to the locational, financial, regulatory, and design constraints that management decisions have to accommodate. That is why technical professionals are necessary for management. However, findings of a scientific study such as this project (which like most other scientific studies forms part of a continuing search for knowledge) can suggest some widely relevant principles and opportunities for analysis that could be used before making some management decisions.

The Merced River in the restored Robinson reach is not a natural river with a natural channel, floodplain, flow and sedimentation regime. This particular restoration project required complete reconstruction of a 3.2 km long floodplain and channel after the destruction of both by decades of gravel mining and the devastating flood of 1997. So the scientific investigations were not designed with natural river functioning in mind. Instead the hydrodynamics and geomorphological part of the study investigated general linkages between the physics of flow, sediment transport, and habitat formation that are likely to apply to many simplified gravel-bed rivers, including those in the early stages of evolution after being radically altered during reconstruction. In this sense, the Robinson reach was used in a manner analogous to a laboratory flume or experimental fish channel. The distinctive research opportunity in the Robinson reach was that it allowed us to examine gradual changes from the original simplified construction. This situation provided the opportunity to observe and analyze which developments can produce favorable habitat values quickly and which developments do not yield benefits in the short term and may need to be avoided or compensated for in future projects. The ecological parts of the study concerned three issues of general significance for river restoration: the aquatic food web and its relationship to fish growth in a simplified river system; the energy budget of Pacific salmon species in various life stages including the juvenile rearing stage; and the constraints on re-vegetating a newly constructed, gravelly floodplain in a semi-arid climate.

Reconstruction of gravel-bed channels on steep valley floors along Central Valley tributaries is a challenging problem, which in some sites may require experimentation with flexible goals. Before European colonization and development, some of these steep valley floors supported multi-thread channels, albeit with more frequent, larger floods than those of the post-dam era. In modern restoration projects, there is a preference for single-thread channels because of the need to concentrate the limited amount of flow available for habitat maintenance and water temperature control in this era of diminished spring and summer flows. Sinuous single-thread channels are also preferred in most restoration projects on grounds of the ease of design and construction, the predictability of likely channel migration, the narrower width of the active channel belt, and ecological concepts of how channel characteristics provide habitat values.

Single-thread channels on such steep gradients promote high sediment transport capacities for particle sizes in the range that favors salmon spawning. Given the low sediment supplies in the post-dam era, this high transport capacity is likely to promote bed coarsening and channel downcutting unless a gravel augmentation maintenance program is committed to for the long term, or undesirably coarse bed sediment is installed, or the channel gradient is kept low by designing a high channel sinuosity. Highly sinuous channels are not characteristic of the region, and the effect of high sinuosity on the development of a channel, and particularly its ability to maintain a stable, single-thread planform, is currently unknown.

The relative steepness of the valley floors also raises the potential for channel avulsion across the valley floor unless preventative maintenance steps are taken. Avulsion and new floodplain channel formation may have positive ecological outcomes in some locations (not the Robinson reach for reasons of local geological site characteristics), but such events are usually considered by river managers and the public to reflect “instability” and are unpopular. Further research on the geomorphological and ecological linkages where new channels are formed by avulsion might lead to more flexible consideration of this issue elsewhere in the region, but the research has not yet been sufficiently compelling to form a basis for recommendations at particular sites.

The need to utilize relatively coarse bed sediment in restoration projects also increases the likelihood that most of the subsequent changes in channel form and bed texture will not occur in the relatively small, frequent floods that are commonly asserted to be the “dominant” channel-forming discharge. Instead, most sediment transport, channel change, and creation of new habitat is likely to occur in larger floods, some of which may be associated with unplanned reservoir releases of unnatural duration. With new tools for modeling of habitat formation and evolution it is now possible to anticipate and evaluate the potential roles of such flood events, as well as the more familiar “two-year flood” events, on the channel and its habitat values. Coarsening of the bed and channel downcutting may also require periodic mitigation through gravel augmentation, and these trends can be predicted and monitored more efficiently than has been possible until recently.

Despite these complications, it is possible to design river reconstruction projects that can remain stable and provide salmon spawning habitat on timescales of decades or more, after which there may be a need for maintenance work (gravel augmentation; bank reinforcement, riparian vegetation). Thus, for projects in developed areas (either in agricultural or urbanizing areas) some form of simple monitoring is a necessity to track when such modifications might be needed. Monitoring and database management have now become faster and cheaper with modern technology, especially with GPS and lidar surveys. For example, denser topographic surveys and automatically analyzed digital photogrammetry of bed texture allow for the quantification of gravel storage or erosion, which can be used to inform if or when gravel augmentation would be necessary. Developing a time-series of high-resolution channel surveys also provides a means of interpreting geomorphically driven changes of habitat quality, such as bar and redd development, bank migration, bank undermining, and microhabitat formation.

In more remote areas, there may not be any need to 'correct' river developments after restoration if changes do not threaten infrastructure or people, and such re-naturalized areas could provide important experiments for observing what might happen in the absence of intensive management elsewhere. However, in more intensively developed areas with considerations of flood potential and channel migration, river managers do not have the luxury of relaxing vigilance.

The task of providing or enhancing spawning resources in restored gravel-bed rivers, at least temporarily, appears to be easier than providing favorable juvenile rearing habitat in the same reaches. Single-thread channel designs usually involve gradients steep enough to provide threshold transport conditions for gravel in a two-year flood (to favor the flushing of fines from gravel redds and the maintenance of loose bed conditions for spawning), and also geometry simple enough to facilitate passage of flood flows and boats. These constraints usually result in flow velocities that are too fast for juvenile salmon to feed and grow even during base flows. Although not so easily documented, the simplicity of the design geometry and the limited time for the development of small-scale complexity, such as undercut banks and channel-margin chutes, in the early post-construction decades also leads to a lack of refuge from predators. Commonly used methods of stabilizing outer channel banks (say) with coarse cobbles and boulders also limits the development of undercut banks and scroll bars on opposite sides of the channel, both of which provide low-velocity zones utilized by juvenile salmon. This and other tensions between designing stable channels and hoping that the river will gradually become more complex over time can now be explored with better models of flow, channel evolution, habitat suitability, and fish growth.

Monitoring and modeling of flow structure, habitat suitability, and channel evolution in the Robinson reach raised the question of whether the prevailing paradigm of the channel flow and sediment supply in an "alluvial" channel providing favorable habitat conditions for every lotic life stage of salmonids is an adequate vision. The interaction between flow and sediment particles tends to create streamlined forms of pools, bars, curved banks, and smoothly varying substrate textures. These features, in turn, establish physical conditions that favor some life-stage activities for fish. However, the literature on the juvenile life stage of Chinook salmon, for example, emphasizes the critical need for low-velocity zones to allow resting and growth close to high-velocity zones, which provide drifting food supplies. Thus, strong velocity gradients are preferred for rearing habitat. Such gradients do not develop often in streamlined geometry, but they are forced on the channel flow field by the presence of non-alluvial structures, such as woody debris and immobile boulders. The most widespread of these features along lowland alluvial streams is large woody debris.

Installing, actively promoting, or even allowing the accumulation of large woody debris in river channels is not universally popular, or desirable, for reasons referred to above. But both the bioenergetic modeling of fish growth and survival and the observations of the limited distributions of juvenile Chinook salmon and resident non-game fish within the Robinson reach indicate reasons to expect significant increases in productive juvenile rearing areas to result from the presence of even small amounts of woody structure in such a simplified habitat. Moreover, the study developed hydrodynamic and ecological modeling tools for exploring and quantifying the positive and negative effects of incorporating such a strategy into some parts of restoration projects. Furthermore, in projects like the Robinson reach, which are not close to vulnerable infrastructure, the potential exists for field-testing and quantification of the potential for such habitat improvements.

The issue of woody debris in the channel, even if it were initially to be installed artificially, brings up the long-term vision of the value to river restoration of accelerating the establishment of a woody riparian zone. Floodplain construction with low water tables and coarse gravel, even if such material formerly supported floodplain forests in the reach, is unlikely to do so today in the diminished hydrologic condition of the valley floor due to reduction or removal of the snowmelt flood. The hydrological results are a lack of water-holding capacity within the gravel and a very high permeability, which ensures that the water table will decline more than a meter below the floodplain surface essentially as rapidly as the river level is reduced (artificially) each spring.

Future planting strategies need to be designed on the basis of more realistic hydrogeological and geomorphological analysis of likely water-table depths and moisture regimes after construction. The widely recognized value of riparian woody vegetation for the quality of fish habitat (related to the provision of woody debris, shade, and food), as well as for other ecological values on floodplains, suggests that in future restoration projects closer linkage be explored between the choice of materials from which to construct the riparian zone, the design depth of the channel, and the methods chosen for ensuring establishment of the woody riparian plants. Analytical tools are available for such explorations. This research project also developed the modeling capacity for examining the tradeoffs between utilizing sediment with greater fines content for constructing the riparian zone and the effect on the fines content of the channel bed.

Despite the complexities of planning river restoration projects, new tools are becoming available for predicting flow characteristics, sediment transport, channel and bed evolution, floodplain changes, and the ecological effects of incorporating structures such as woody debris into channel designs. The gradual accumulation of successfully validated predictions increases confidence in the use of these tools for exploring a broader range of design options and long-term habitat evolution than was formerly possible. Ecological modeling tools and field experimental methods are also available, but are used less frequently for reducing uncertainty and developing ecological understanding and for planning and designing river restoration.

PROJECT DELIVERABLES

- List here any presentations given at the Bay-Delta Science Conference and at other events

The following symbols indicate contributors to the project in addition to the PIs:

*** high-school intern**
§ undergraduate research assistant
† PhD student
‡ postdoc

Bay-Delta Science Conference Presentations (BDS)

1. ‡Harrison, L.R., Dunne, T. and †Fischer, G.B. (2012). Hydraulic interactions between a meandering river channel and its floodplain during an overbank flood. 7th Biennial *California Bay-Delta Science Conference*, Sacramento, CA.
2. †Albertson, L.K., Cardinale, B.J., ‡Zeug, S.C., †Wydzga, A., ‡Harrison, L., Lenihan, H.S. and Dunne, T. (2008). Geomorphic constraints on the restoration of macroinvertebrate assemblages in the Merced River, CA, 5th Calfed Science Conference, Sacramento, CA.
3. ‡Harrison, L.R., †Legleiter, C.J., †Wydzga, M.A. and Dunne, T. (2008). Reach-scale morphologic and ecologic response to restoration in a simplified river channel-floodplain system. 5th Biennial *CALFED Science Conference*, Sacramento, CA.
4. †Soong, O., Dulik, K., ‡Harrison, L., and Davis, F. (2008). Site and management effects on riparian vegetation development on the restored floodplain of the Merced River, California. 5th Biennial CALFED Science Conference, October 22-24, 2008.
5. †Wydzga, M.A., ‡Harrison, L.R., †Legleiter, C. and Dunne, T. (2008). Predicting Bed Mobility in a Simple River Channel: Implications for River Management and Restoration. 5th Biennial CALFED Science Conference; Sacramento, CA.
6. †Constantine, C.R., Dunne, T., Singer, M.B. and Chang, H.H. (2006). A bed-material sediment budget for the Sacramento River from Red Bluff to Colusa and its relation to rates of meander migration. 4th Biennial *California Bay-Delta Science Conference*, Sacramento.
7. †Legleiter, C.J., †Wydzga, M.A., Faulkenberry, K., Encinas, D., Kyriakidis, P.C. and Dunne, T. (2006). Morphologic response of a restored, gravel-bed reach of the Merced River to sustained high flows. 4th Biennial CALFED Science Conference, Sacramento.

Other Conference Presentations (OCP)

1. Dunne, T. (2009) River migration and floodplain complexity. Annual Meeting, Japanese Geomorphological Union, Kyoto, Oct. 2009.
2. Dunne, T. (2010) River Restoration in the United States: Research Challenges, Zheijang Univ., Hangzhou, China, Sept., 2010.
3. Dunne, T. (2011) The role of sediment in river restoration, Keynote Lecture, Northwest River Restoration Symposium, Portland, OR, Feb., 2011.
4. Dunne, T. (2012) The evolution of floodplain complexity Wolman Lecture, Annual Meeting, Consortium of Universities for the Advancement of Hydrological Sciences, Inc., Boulder, CO, July, 2012.
5. ‡Harrison, L.R., Dunne, T. and †Fischer, G.B. (2012). Development of habitat complexity in a meandering river-floodplain system. *Fall Meeting of the American Geophysical Union*, San Francisco, CA.
6. ‡Harrison, L.R., ‡Hafs, A., ‡Utz, R. and Dunne, T. (2013). Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon. *Fall Meeting of the American Geophysical Union*, San Francisco, CA.
7. ‡Harrison, L.R., †Legleiter, C.J., †Albertson, L.K., Dunne, T., Cardinale, B.J. and †Wydzga, M.A. (2009). The role of sediment supply on channel morphology, habitat availability and food web dynamics.

Defining Hydromorphological Condition and Links to Ecology: An International Workshop. Ballater, Scotland.

8. ‡Harrison, L.R., †Legleiter, C.J., ‡Pecquerie, L. and Dunne, T. (2009). Channel dynamics and habitat complexity in a meandering, gravel-bed river. *Fall Meeting of the American Geophysical Union*, San Francisco, CA.
9. ‡Harrison, L.R., †Legleiter, C.J., †Wydzga, M.A. and Dunne, T. (2008). Quantifying the co-evolution of morphology, flow hydraulics and Chinook spawning habitat in a recently restored gravel-bed river. Eos Trans. AGU, 89(53), Fall Meet. Suppl., H42A-04.
10. ‡Harrison, L.R., †Legleiter, C.J., †Wydzga, M.A. and Dunne, T. (2009a). Evolution of physical and ecological processes in a simplified gravel-bed river. *7th International Ecohydraulics Conference*, Concepcion, Chile.
11. ‡Harrison, L.R., Legleiter, C.J., Wydzga, M.A. and Dunne, T. (2009b). Channel dynamics and habitat complexity in a meandering, gravel-bed river. Fall meeting of the American Geophysical Union, San Francisco.
12. ‡Harrison, L.R., Nisbet, R.M., Anderson, K.E. and ‡Pecquerie, L. (2010). Linking two-dimensional flow with invertebrate drift transport. *University of California, Davis Instream Flow Assessment Workshop*, Davis, CA.
13. †Legleiter, C.J. (2007). Quantifying the spatial variability of river morphology and hydraulics in natural and restored gravel-bed rivers. Annual Meeting of the Association of American Geographers, San Francisco.
14. †Legleiter, C.J., ‡Harrison, L.R. and Dunne, T. (2010). Effect of point bar development on the local force balance governing flow in a simple, meandering gravel-bed river. Annual meeting of the Association of American Geographers, Washington, D.C.
15. †Legleiter, C.J., Kyriakidis, P.C., McDonald, R.R., and Nelson, J.M. (2009). Effects of uncertain topographic input data on two-dimensional modeling of flow hydraulics, habitat suitability, and bed mobility. Fall meeting of the American Geophysical Union, San Francisco.
16. Nisbet, R.M. (2010), Population response length: theory and applications, Workshop on Modeling, Understanding and Managing River Ecosystems University of Ottawa.
17. Nisbet, R.M. (2011). A Salmon's Perspective on Spatial Ecology. Workshop on Emerging Challenges at the Interface of Mathematics, Environmental Science and Spatial Ecology, Banff International Research Station.
18. Nisbet, R. M., ‡Pecquerie, L., ‡Harrison, L. and Anderson, K. (2010). *Integrating Bionenergetics, Spatial Scales and Population Dynamics for Environmental Flow Assessments.* Instream flow assessment workshop, UC Davis, December 2010.
19. †Soong, O. and Davis, F. (2011). Seedling recruitment of riparian trees along the Merced River, CA: Safe sites and tolerance. 96th Ecological Society of America Annual Meeting, August 12, 2011.
20. †Soong, O., Dulik, K., Castro, L., Hendrickson, B., Moise, G. W., and Davis, F. (2007). Site, management, and plant species effects on riparian vegetation development on a restored floodplain of the Merced River, California. Ecological Society of America/Society for Ecological Restoration Joint Meeting, August 5-10, 2007.
21. †Soong, O., ‡Harrison, L., and Davis, F. (2009). Coupling of riparian tree recruitment and river hydrology along a recently restored reach of the Merced River, CA. 94th Ecological Society of America Annual Meeting, August 6, 2009.

22. ‡Stover, J.P. (2012) *Heterogeneity in dispersal and the spread of populations.* 97th Annual Meeting of the Ecological Society of America, Portland, OR, Aug 2012.

- List here and provide hardcopies and electronic files of all materials and published papers resulting from this grant

Published Articles (PA) (pdfs attached)

1. †Albertson, §L.K., Koenig, §L.E., Lewis, B.L., ‡Zeug, S.C., ‡Harrison, L.R. and Cardinale, B.J. (2012). How does restored habitat for Chinook salmon (Oncorhynchus tshawytscha) in the Merced River, California compare to other Chinook streams? *River Research and Applications*. doi: 10.1002/rra.1604.
2. †Albertson, L.K., Cardinale, B.J., ‡Zeug, S.C., ‡Harrison, L.R., Lenihan, H.S. and †Wydzga, M.A. (2010). Impacts of channel reconstruction on invertebrate assemblages in a restored river. *Restoration Ecology*, 19:627-638. doi: 10.1111/j.1526-100X.2010.00672.x.
3. Anderson, K.E., ‡Harrison, L.R., Nisbet, R.M., ‡Kolpas, A. (2013) Modelling the influence of flow on invertebrate drift across spatial scales using a 2D hydraulic model and a 1D population model. *Ecological Modelling*, 265: 207-220. doi.org/10.1016/j.ecolmodel.2013.06.011.
4. Dunne, T. and Aalto, R.E., 2013. Large river floodplains. In: Shroder, J. (Editor in Chief), Wohl, E. (Ed.), Treatise on Geomorphology, vol. 9, Fluvial Geomorphology, pp. 645–678, Academic Press, San Diego, CA.
5. Dunne, T., Constantine, J.A. and Singer, M.B. (2010). The role of sediment transport and sediment supply in the evolution of river channel and floodplain complexity. Transactions, Japanese Geomorphological Union, 31-2, p. **155-170.**
6. ‡Harrison, L.R., †Legleiter, C.J., †Wydzga, M.A. and T. Dunne. 2011. Channel dynamics and habitat development in a meandering, gravel-bed river. *Water Resources Research*. doi:10.1029/2009WR008926.
7. ‡Kolpas, A. and Nisbet, R.M. (2010). Effects of Demographic Stochasticity on Population Persistence in Advective Media. *Bulletin of Mathematical Biology* 72: 1254-1270. doi: 10.1007/s11538-009-9489-4
8. †Legleiter, C.J., ‡Harrison, L.R. and Dunne, T. (2011). Effect of point bar development on the local force balance governing flow in a simple, meandering gravel-bed river. *Journal of Geophysical Research – Earth Surface*. doi:10.1029/2010JF001838.
9. ‡Pecquerie, L., †Johnson, L.R. and Nisbet, R.M. (2011). Analyzing variations in life-history traits of Pacific salmon in the context of Dynamic Energy Budget (DEB) theory, *Journal of Sea Research*: 66: 424-433. doi:10.1016/j.seares.2011.07.005
10. *Romanov, A. M., §Hardy, J., ‡Zeug, S. C. and Cardinale, B. J. (2012) Abundance, size structure, and growth rates of Sacramento pikeminnow (*Ptychocheilus grandis*) following a large-scale stream channel restoration in California. Journal of Freshwater Ecology, 27(4) 495-505. doi**:** 10.1080/02705060.2012.674684
11. ‡Utz, R. M., Mesick, C. F., Cardinale, B. J., and Dunne, T. (2013). How does *artificially coarse gravel augmentation impact early-stage Chinook salmon* (Oncorhynchus tshawytscha) embryonic survivorship? Journal of Fish Biology, 82, 1484-1496. doi:10.1111/jfb.12085. doi:10.1111/jfb.12085

12. ‡Utz, R. M., Zeug, ‡S. C. and Cardinale, B. J. (2012) Juvenile Chinook salmon (Oncorhynchus tshawytscha) growth and diet attributes in riverine habitat engineered to improve conditions for adults. Fisheries Management and Ecology, 19, 1-14, 2012. doi: 10.1111/j.1365-2400.2012.00849.x
13. ‡Utz, R. M., ‡Zeug, S.C., Cardinale, B. J. and †Albertson, L.K. (2012). Trophic ecology and population attributes of two resident non-game fishes in riverine habitat engineered to enhance salmon spawning success. California Fish and Game, 98 (2), 104-124.
14. ‡Zeug, S. C., †Albertson, L. K., Lenihan, H., §Hardy, J. and Cardinale, B. J. (2011). Predictors of Chinook salmon extirpation in California's Central Valley. Fisheries Management and Ecology, 18:61-71.

Manuscripts In Review (R)

1. §Hafs, A., §Harrison, L.R., §Utz, R. and Dunne, T. (In review) Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon. *Ecological Modelling*.
2. †Soong, O. and Davis, F. (In review). Restoring floodplain herbaceous communities in Mediterranean-climate California. Restoration Ecology.
3. §Stover, J.P., Kendall, B.E. and Nisbet, R.M. (in review). Consequences of dispersal, heterogeneity for population spread and persistence. *Bulletin of Mathematical Biology*.

Manuscripts in Preparation (P)

1. §Harrison, L.R., Dunne, T. and †Fischer. G.B. (In prep.) Hydraulic and geomorphic significance of overbank flow along a meandering gravel-bed river. *Earth Surface Processes & Landforms*.
2. †Soong, O. and Davis, F. (In prep.) In situ recruitment and the recruitment box model.